NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 274

THE N. A. C. A. PHOTOGRAPHIC APPARATUS FOR STUDYING FUEL SPRAYS FROM OIL ENGINE INJECTION VALVES AND TEST RESULTS FROM SEVERAL RESEARCHES

By EDWARD G. BEARDSLEY

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	sec	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/sec		horsepower	HP.
Speed		km/hr		mi./hr	M. P. H.
		m/sec		ft./sec	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight, $=mg$

g, Standard acceleration of gravity $=9.80665$ m/sec.$^2=32.1740$ ft./sec.^{2}

m, Mass, $=\frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} sec.^{2}) at 15° C and 760 mm $=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m$^3=0.07651$ lb./ft.^{3}

mk^2, Moment of inertia (indicate axis of the radius of gyration, k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord length.

b/c, Aspect ratio.

f, Distance from $c.\ g.$ to elevator hinge.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C.)

i_w Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting with reference to thrust line.

γ, Dihedral angle.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;

or for a model of 10 cm chord 40 m/sec, corresponding numbers are 299,000 and 270,000.

C_p, Center of pressure coefficient (ratio of distance of $C.\ P.$ from leading edge to chord length).

β, Angle of stabilizer setting with reference to lower wing, $=(i_t-i_w)$.

α, Angle of attack.

ϵ, Angle of downwash.

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By Edward G. Beardsley

SUMMARY

Apparatus for recording photographically the start, growth, and cut-off of oil sprays from injection valves has been developed at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics. The apparatus consists of a high-tension transformer by means of which a bank of condensers is charged to a high voltage. The controlled discharge of these condensers in sequence, at a rate of several thousand per second, produces electric sparks of sufficient intensity to illuminate the moving spray for photographing. The sprays are injected from various types of valves into a chamber containing gases at pressures up to 600 pounds per square inch.

Several series of pictures are shown. The results give the effects of injection pressure, chamber pressure, specific gravity of the fuel oil used, and injection-valve design, upon spray characteristics.

INTRODUCTION

The first successful compression-ignition oil engine, using air injection, was built about 1897, by Doctor Diesel. About 1912, McKechnie constructed a practicable so-called solid or hydraulic injection engine. Since that time the solid-injection engine has been gradually developed and the demand for it has so increased that to-day a large number of engine builders are manufacturing this type. Much progress has been made, and a great deal of knowledge has been gained concerning solid-injection engines.

The part of the engine about whose operation we have the least information thus far, is probably one of the most important parts, namely, the injection valve. Sprays from injection valves have been examined in the atmosphere as to their cone angle, fineness of atomization, and rapidity of combustion when ignited. They have been injected into water and the penetration noted visually. However, the complete behavior of a spray injected into dense air has always been a matter for conjecture and theoretical computation. (Reference 1.) Yet it is something which is very important, and because of this lack of definite knowledge, the design of an injection valve to give the best results in a particular combustion chamber has been to a large degree a process of cut and try.

A study of the compression-ignition, solid-injection type of engine, with regard to its possible development for aircraft use was started at the Langley Memorial Aeronautical Laboratory at Langley Field, Va., in 1921. The general problem was analyzed and an attempt made to attack it from all angles. Actual knowledge about the characteristics of sprays from injection valves was desired. While the adaptability of the spray to the combustion chamber is not of so much importance in the case of a low-speed, low-capacity engine, it is vital for the high-speed, high-capacity engine useful for aircraft. The spray was therefore to be studied with regard to its penetration, general shape, and atomization when injected into dense air.

It was concluded that the method by which it would be possible to obtain the greatest amount of information about oil sprays was to take high-speed motion pictures of their start,

development, and cut-off, which would show their penetration, general shape, and possibly their atomization. With this end in view, preliminary apparatus was designed, built, and tested during the summer of 1921. However, it was found impossible to obtain a series of pictures of oil sprays with this apparatus. Finally, in the fall of 1924, the photography of oil sprays in dense air became a reality. From that time to the present day much improvement has been made in the apparatus and methods, and considerable knowledge has been gained concerning the several factors governing the characteristics of oil sprays.

DESCRIPTION OF THE N. A. C. A. SPRAY PHOTOGRAPHY APPARATUS

DEVELOPMENT OF THE APPARATUS

The problems involved in taking moving pictures of oil sprays from injection valves presented numerous difficulties. The two outstanding problems were: The necessity of having a duration of exposure of about a millionth of a second; and the production of photographic records, with this short exposure, at a rate of several thousand a second. The extremely short

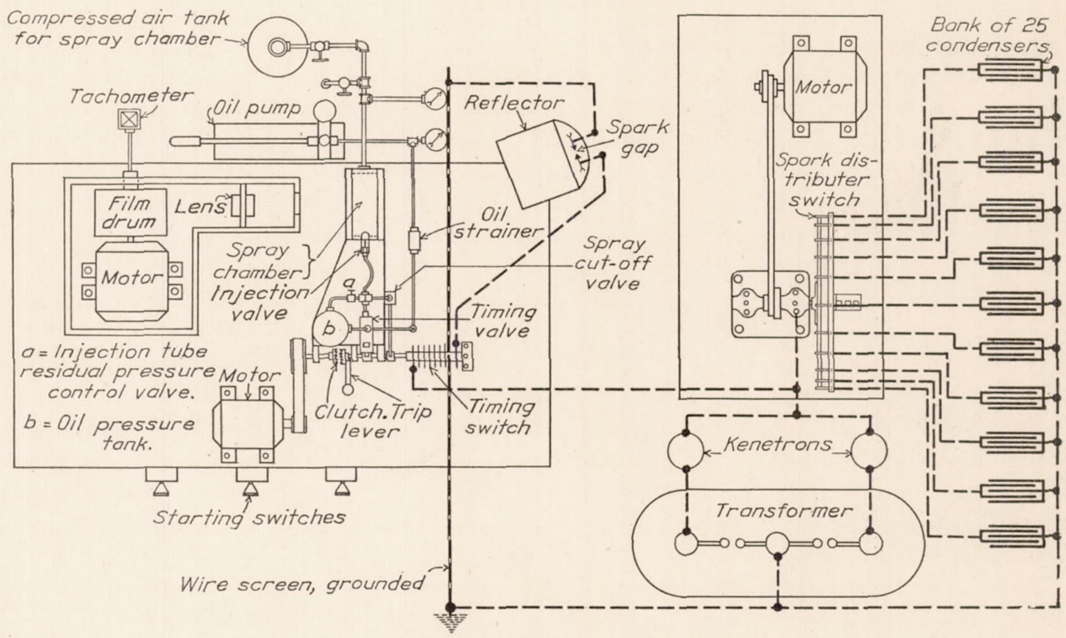


FIG. 1.—Diagrammatic arrangement of spray-photography apparatus

duration of exposure necessary can be computed by assuming that the spray has an initial velocity of 500 feet per second, or 6,000 inches per second, and permitting a distortion of one one-hundredth inch of the spray image recorded on a photographic film. For these conditions the duration of exposure must not be more than one six-hundred-thousandth second. It is evident that it would be practically impossible to build a mechanically operated shutter which would give such a brief exposure. Also, with this infinitesimal duration of exposure, the illumination must be very intense in order to produce a satisfactory record on the film. The only solution of the problem seemed to be to use the discharge of electrical condensers, the duration of the spark from a condenser discharge being known to be of the short time required, thus eliminating mechanical shutters.

The next requirement was that the series of pictures of the spray be taken at a rate of several thousand per second. This necessitated the use of a number of condensers arranged so that they could be discharged at the required frequency.

The first electrical system investigated consisted of 15 Leyden jars, which were charged by a static machine. Because of the dampness of the climate the machine failed to charge satisfactorily.

A 100,000-volt transformer and kenotron rectifying tubes were next installed. Fifteen 30 by 30 inch glass-plate condensers were built, but were unsuccessful because of excessive surface leakage and frequent puncturing of the glass plates. Twenty-five condensers were then built with Micanite plates for dielectrics. These have proved to be successful.

The present spray-photography apparatus, so far as is known, was the first apparatus ever built capable of recording by a series of pictures the growth of oil sprays. A diagramatic layout of the apparatus is shown in Figure 1, and a general view is shown in Figure 2. The electrical apparatus consists of a high-tension transformer, two kenotron rectifying tubes, a bank of 25 condensers, a rotating distributor switch, a timing switch, and a spark gap in front of a

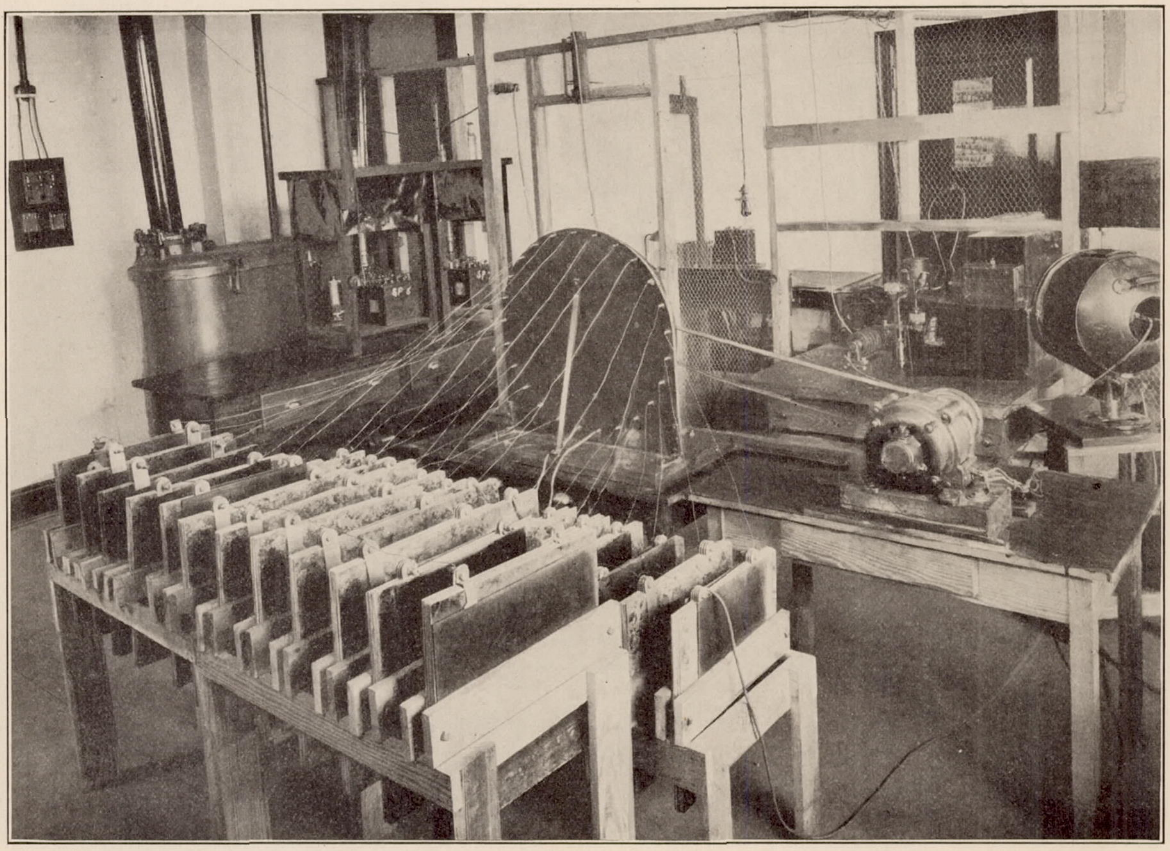


FIG. 2.—GENERAL VIEW OF SPRAY-PHOTOGRAPHY APPARATUS

reflector for focusing the light on the moving oil spray. Figures 1 and 2 show the transformer and kenotron rectifying tubes, by means of which the 25 condensers are charged to 30,000 volts through the rotating distributor switch. One terminal of each condenser is connected to a contact on the switch panel, and the other is grounded. Discharge across the spark gap can not take place until the timing switch operated by the cam shaft is rotated, when each condenser is discharged in sequence across the gap. The frequency of the discharges is controlled by the speed of rotation of the distributor switch. This switch is of the rotating, multiple-break type, by means of which it is possible to make and break a high-tension circuit without serious arcing.

THE INJECTION SYSTEM

The apparatus for the production and control of sprays is shown diagrammatically in the left-hand half of Figure 1. It consists of a high-pressure, hydraulic hand pump, a pressure tank, timing valve, cut-off valve, initial-pressure control valve, motor-driven cam shaft, and spray chamber.

The hydraulic hand pump used is of the ordinary plunger type and is capable of delivering oil at pressures up to 12,000 pounds per square inch. The pressure tank provides a sufficient volume of oil to insure a practically constant pressure on the oil during the whole injection period. The timing valve consists of a spring-loaded needle valve which is lifted from its seat by a cam-operated lever. The cut-off valve is a poppet valve actuated by another cam-operated lever. The duration of injection is controlled by adjusting the lever along the cam so as to obtain earlier or later operation of the cut-off valve with respect to the timing valve. The mechanism is so designed that the amount and rate of opening of the valve is practically constant for all cut-off positions of the lever. The initial-pressure control valve, when opened, allows oil to be pumped directly into the injection-valve tube, either for testing the opening pressure of the valve or to provide the correct initial pressure in the injection-valve tube before injection.

The shaft carrying one-half of the jaw clutch is driven at 900 revolutions per minute by a motor. The clutch is similar to the type used on punch presses, and is so arranged that when the trip lever is struck the two halves of the clutch engage and the hollow shaft carrying the cams is given one revolution. The timing switch is connected to the cam shaft by means of a serrated coupling and can be turned so that it will make contact at the proper time to synchronize the beginning of the sparks with the beginning of the spray.

The spray chamber is of cast iron, two sides of which are formed by frames holding optical-glass windows 1 inch thick supported on rubber. The window frames are bolted on and sealed with rubber gaskets. Gas pressures up to 600 pounds per square inch are used in the chamber.

THE RECORDING APPARATUS

The recording apparatus consists of a camera box containing a lens and a motor-driven film drum. To concentrate the light of the spark upon the spray a reflector is used. It will be noted from Figure 1 that it is offset from the line of the chamber and film drum. Only the light refracted and reflected by the spray itself passes in through the lens and records the series of pictures of the moving spray upon the film. The film is fastened around a drum 30 inches in circumference, which is mounted on the shaft of an electric motor. The speed of rotation of the film, together with the rate of discharge of the condensers, determine the spacing of pictures. An F:2 lens is used. All pictures of the sprays are taken half-size on commercial photographic roll film.

Apparatus, not shown in Figure 1, is used to determine the time lag between the opening of the timing valve and the opening of the injection valve, as shown by the appearance of the spray. It consists of a mirror which is rotated by the opening of the timing valve and deflects a light beam reflected by it onto a moving film. The time lag between the start of opening of the timing valve and the start of the spray is obtained by means of timing lines marked on the film by a one sixty-fourth-inch spark gap in series with the main spark gap.

OPERATION OF APPARATUS

The operation of the apparatus is as follows: The initial pressure in the injection valve tube is adjusted, after which the control valve is closed. Oil is pumped into the pressure tank to the test pressure, and the air pressure in the spray chamber is adjusted. All test conditions being obtained, the clutch trip lever is struck. The timing valve opens, allowing oil under high pressure to pass to the injection valve and open it, causing a spray to shoot across the chamber. The cut-off valve then opens after the required time interval, releases the pressure, and causes the injection valve to close and cut off the spray. The timing switch is closed when the timing valve is opened and the condensers are discharged across the gap, a series of 25 pictures being taken of the start, development, and cut-off of the spray.

TEST RESULTS FROM SEVERAL RESEARCHES WITH THE SPRAY PHOTOGRAPHY APPARATUS

RANGE OF INVESTIGATIONS

Various researches have been carried on with the present apparatus to determine the effects of injection pressure, chamber pressure, and gas density, fuel oil used, and injection-valve design, on oil sprays. Thus the development of single sprays with time, their velocities, penetrations, distribution, form, spray-cone angles, actual volumes, and relative atomization are determined for various types and designs of injection valves. Several phenomena connected with injection hydraulics also have been investigated.

The injection valves studied include mechanically operated valves, and automatic-injection valves especially developed for high-speed operation. The sprays are discharged from round orifices with or without directing impact surfaces and through annular orifices. Spiral grooves with helix angles of from 23° to 90° have been used to break up the spray by means of centrifugal force. The former groove angle gives a spray to which about the maximum amount of centrifugal force practicable has been applied, while the latter gives a noncentrifugal spray.

Descriptions of the injection valve and the valve assemblies used in obtaining Figures 3 to 7 are given in Reference 1.

SPRAY PHOTOGRAPHS

Figure 3 shows a complete spray from an injection valve employing medium centrifugal force. The injection pressure was 8,000 pounds per square inch, and the chamber-air pressure was 200 pounds per square inch. The actual penetration of the moving spray in inches and the time in thousandths of a second from the start of injection are given by the scales. The start of cut-off is marked.

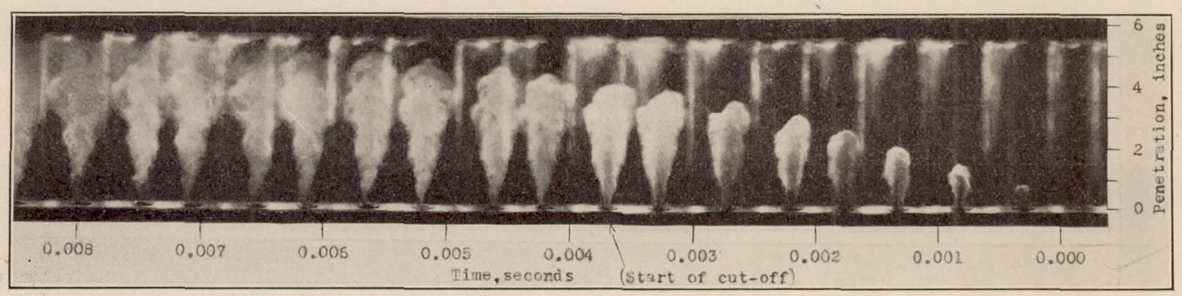


FIG. 3. MEDIUM CENTRIFUGAL SPRAY FROM INJECTION VALVE No. 7

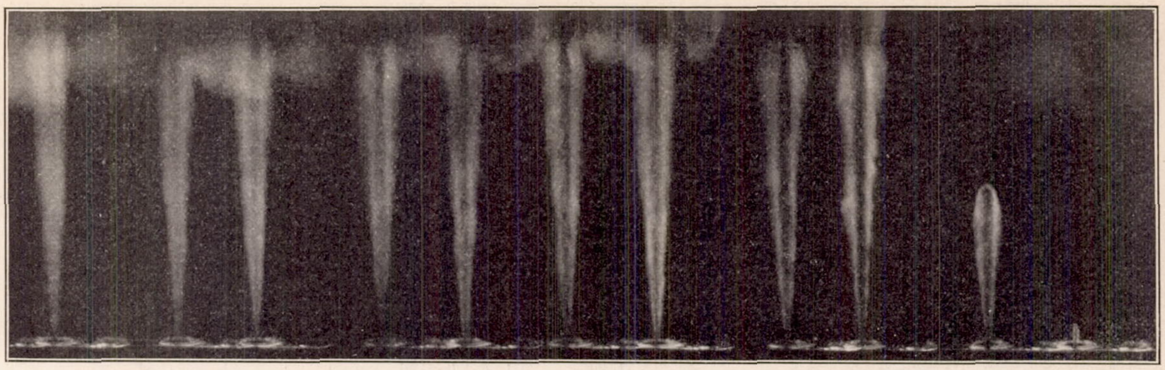
Diesel oil of 0.85 specific gravity injected at 8,000 pounds per square inch into compressed air at 200 pounds per square inch

The following information is obtained from series of pictures similar to the above:

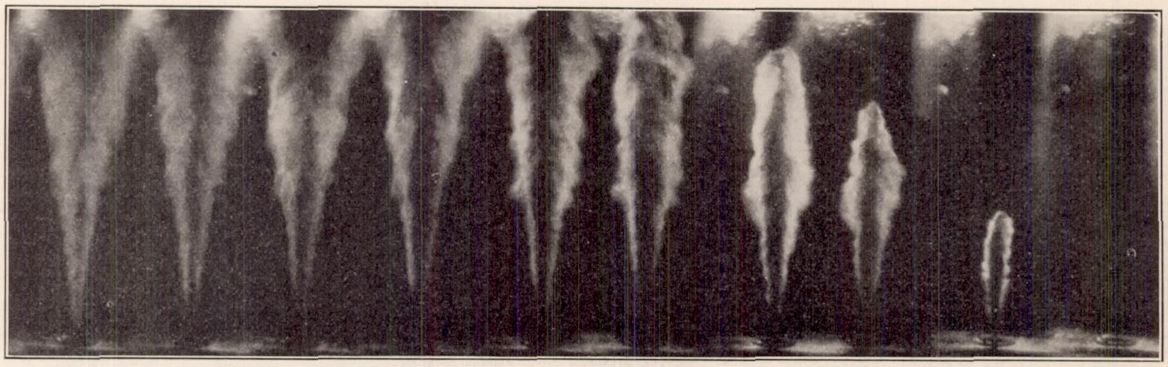
Visual studies	Measurements and computations	Effects of variables
General spray form	Spray penetration with time	Effects of injection pressure.
Peculiarities in spray form	Time of cut-off after spray starts	Effect of chamber gas density.
Cut-off	Spray cone angle	Effects of specific gravity of fuel oil.
Phenomena occurring after cut-off	Volumetric growth of spray	Effect of injection valve design.
Atomization of spray	Spray distribution	Effect of injection system.

The end of the spray after cut-off appears somewhat like a corkscrew. This spiral appearance is probably caused by whirling of the oil drops which have passed around spiral grooves inside the valve, and continues after the oil has left the valve in spray form. It will be noted that the spray seems to have lost its motion in the last few pictures, especially at the nozzle where the spray is practically hanging motionless in mid-air.

In Figure 4 are shown noncentrifugal sprays from a cylindrical orifice injected at 8,000 pounds per square inch pressure into the atmosphere and into 200 pounds per square inch air pressure. The sprays appear somewhat like fir trees with drooping branches. This is because the velocity of the drops of oil is practically zero at the outside of the spray and increases toward the center. The oil seems to shoot out through the center and spill over on the sides, much like a fountain of water. On the sides of the sprays clouds of oil particles appear as bumps,

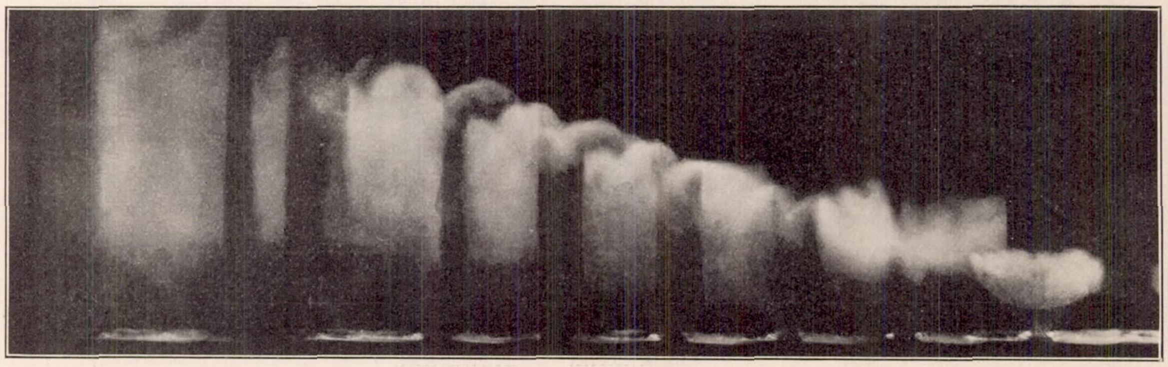


Injection pressure, 8,000 pounds per square inch   Chamber pressure, atmospheric

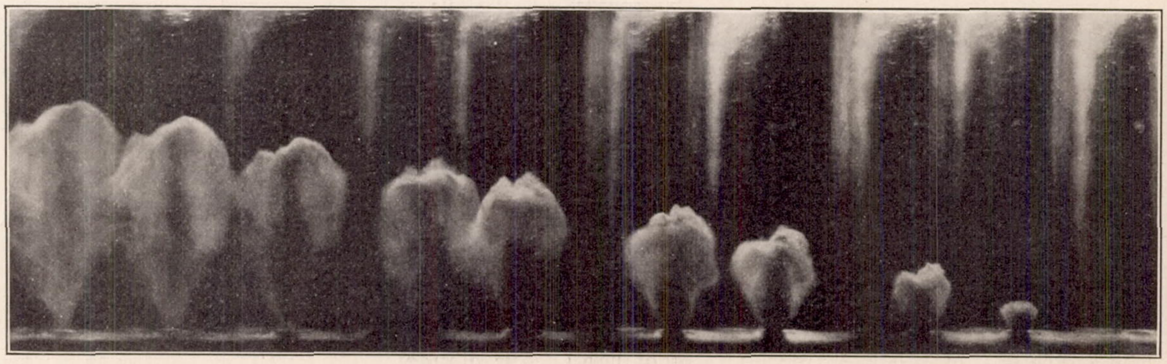


Injection pressure, 8,000 pounds per square inch   Chamber pressure, 200 pounds per square inch

FIG. 4.—EFFECT OF CHAMBER PRESSURE ON NONCENTRIFUGAL SPRAY

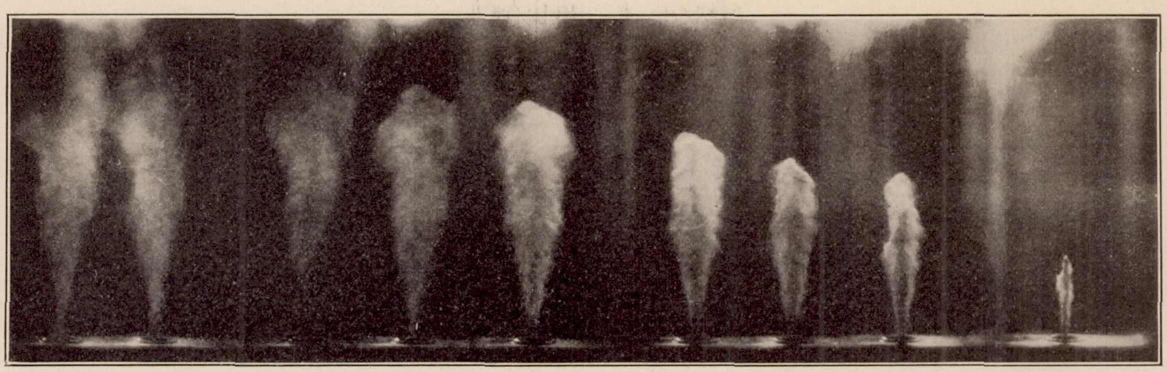


Injection pressure, 8,000 pounds per square inch   Chamber pressure, atmospheric

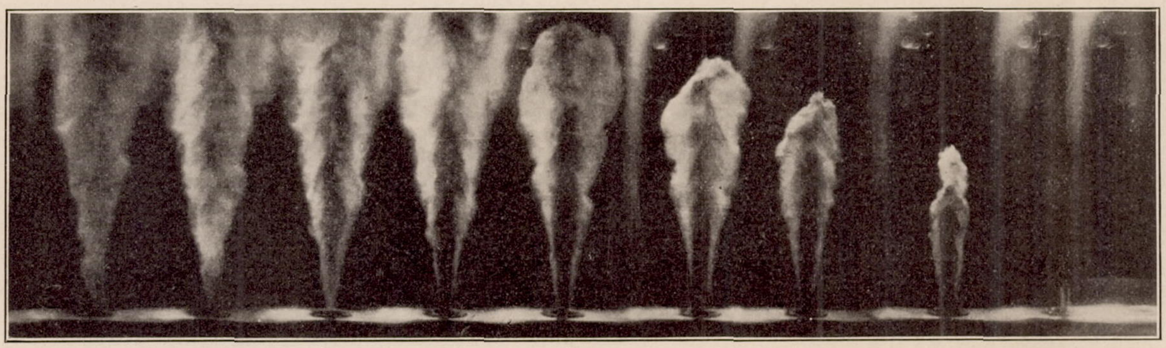


Injection pressure, 8,000 pounds per square inch   Chamber pressure, 200 pounds per square inch

FIG. 5.—EFFECT OF CHAMBER PRESSURE ON HIGH CENTRIFUGAL SPRAY

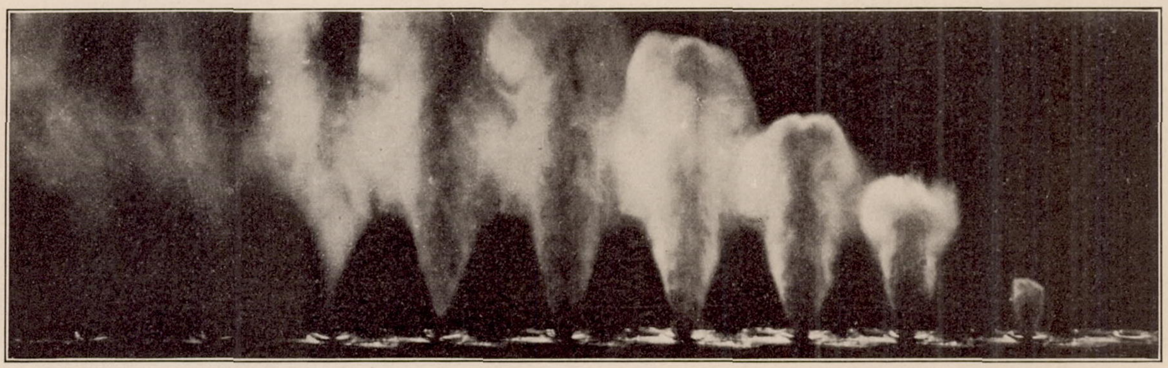


Injection pressure, 8,000 pounds per square inch Chamber pressure, 200 pounds per square inch
Ratio of orifice area to groove area, 0.19
Orifice area, 0.000113 square inch

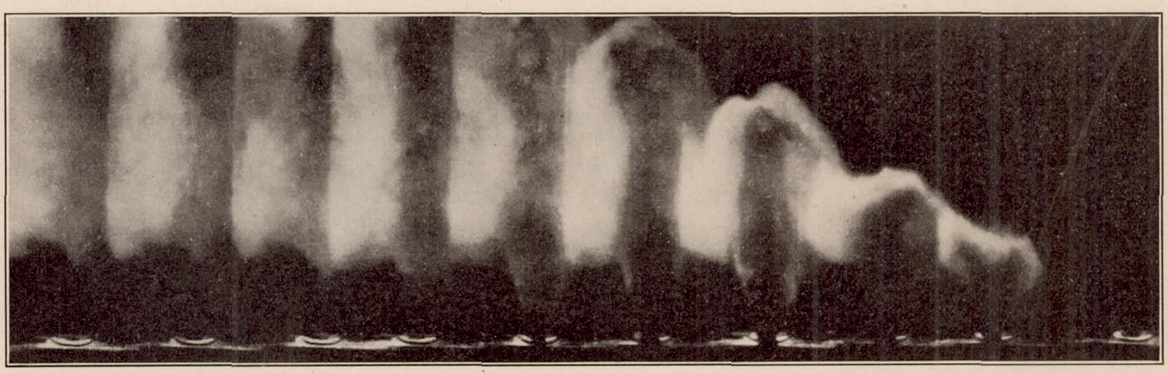


Injection pressure, 8,000 pounds per square inch Chamber pressure, 200 pounds per square inch
Ratio of orifice area to groove area, 0.19
Orifice area, 0.00038 square inch

FIG. 6.—EFFECT OF VALVE SIZE UPON CENTRIFUGAL SPRAY



Injection pressure, 8,000 pounds per square inch Chamber pressure, atmospheric
Centrifugal spray with secondary discharge after cut-off



Injection pressure, 8,000 pounds per square inch Chamber pressure, atmospheric
Centrifugal spray with no secondary discharge after cut-off

FIG. 7.—CENTRIFUGAL SPRAYS WITH AND WITHOUT DISCHARGE AFTER CUT-OFF

which do not change their position from one picture to another. They show that the oil particles at the outside of the sprays are motionless. The spray-cone angle was increased 50 per cent by injection into dense air. The atomization also appears to be increased, as shown by the pictures.

High-centrifugal sprays injected into the atmosphere and into 200 pounds per square inch air pressure are shown in Figure 5. The reduction in the spray angle with the spray injected into dense air is about 40 per cent. This may well explain the failure of some centrifugal valves to operate successfully in an engine when the spray appeared well suited for the engine combustion chamber from observations made in the atmosphere. This decrease of spray-cone angle is characteristic of all centrifugal sprays.

In Figure 6 are two sprays injected into 200 pounds per square inch air pressure, which show what might be called scale effect; that is to say, the ratio of orifice area to groove area is the same for both, but a larger orifice and corresponding grooves were used for the second spray, and as a result the quantity of oil injected was over three times as great.

Figure 7 shows a spray which has a small secondary spray discharge taking place after cut-off. This phenomenon is thought to be caused by a pressure wave in the oil line, and was eliminated in the second series of pictures by increasing the length of the injection-valve tube, thus damping out the pressure wave.

The penetration-time curves are plotted from data computed from measurements of the spray images on each film, taking into account the film speed and photographic reduction as has been done in computing the scales on the pictures in Figure 3. The spray volumes are computed by summation of the differential cylinders making up each spray.

EFFECT OF INJECTION PRESSURE

Figure 8 shows the effect of injection pressures of from 2,000 to 8,000 pounds per square inch on the penetration of sprays, from a 0.0155 inch diameter round orifice, injected into 200 pounds per square inch air pressure. The curves are almost straight and parallel, which shows that the penetration increased nearly in proportion to the injection pressure. This is a charac-

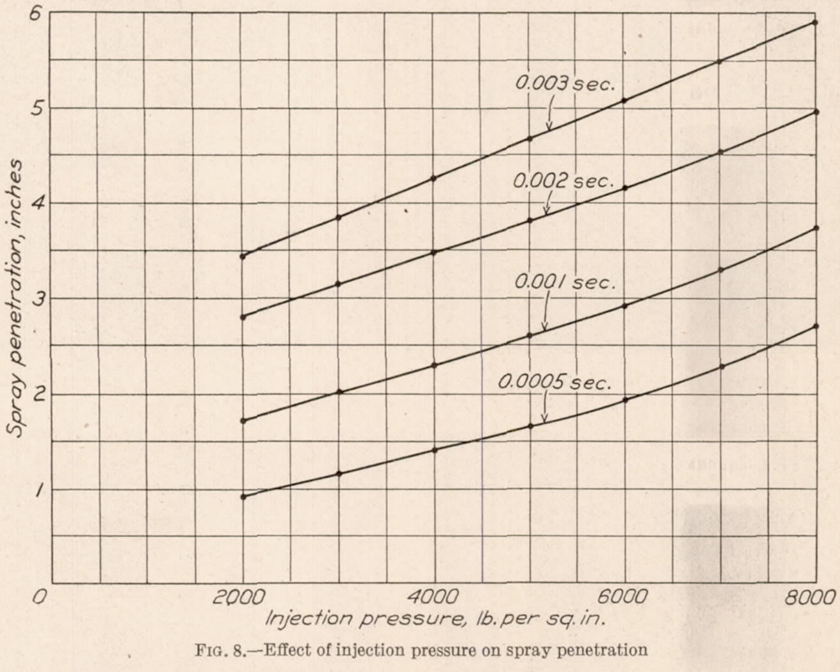


FIG. 8.—Effect of injection pressure on spray penetration

Cylinder orifice, 0.0155 inch diameter.
Fuel oil used, Diesel oil of 0.85 specific gravity.
Nitrogen in spray chamber at 200 pounds per square inch.

teristic result. There is a limit beyond which increase in the injection pressure would not increase the penetration and might even decrease it. This limit is reached when the drops are atomized so finely as to be too light to penetrate the dense air. The injection pressure affects the spray-cone angle as well as the penetration. Increase in the injection pressure causes a narrower spray-cone angle with a noncentrifugal valve, and a wider spray-cone with a high-centrifugal valve.

EFFECT OF GAS DENSITY

Figure 9 shows the effect of chamber-gas pressure and density upon the spray penetration after 0.001, 0.002, and 0.003 seconds. The main curves were cross-plotted from the curves shown in the insert, which are for nitrogen gas, and from similar curves obtained with helium and carbon dioxide gas in the chamber. Each point is labeled as to the gas which was used in obtaining it. The points obtained by injection into the various gases were all plotted on a basis

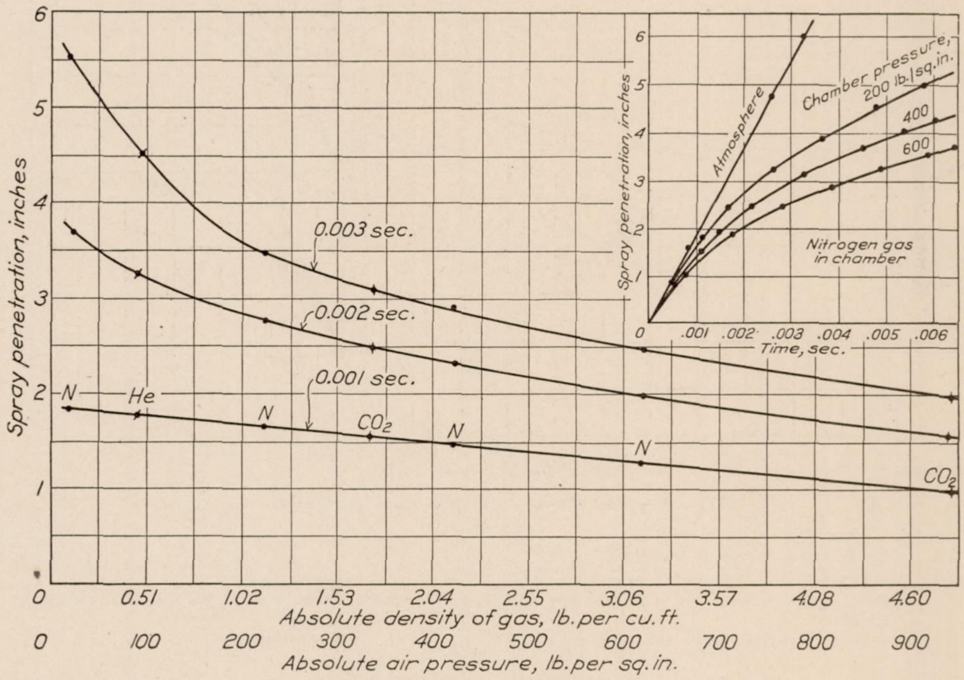


FIG. 9.—Effect of gas density on spray penetration

Injection valve No. 7; 23° spiral grooves.
Cylinder orifice, 0.022 inch diameter.
Injection pressure, 8,000 pounds per square inch.
Fuel used, Diesel oil of 0.85 specific gravity.
Gas in spray chamber, nitrogen, carbon dioxide, or helium.

of absolute gas density. As all of the points lie on the curves, this shows that it is the absolute density of the gas which controls spray penetration, that the viscosity of the gases has no appreciable effect, and pressure affects the penetration only in so far as it controls the density. This indicates that it is the density of the gas which controls spray penetration in an engine cylinder and not the compression pressure.

EFFECT OF SPECIFIC GRAVITY OF FUEL OIL

Figure 10 shows the effect of the specific gravity of the fuel used upon the spray penetration after 0.001, 0.002, 0.003, and 0.004 seconds, with a high-centrifugal valve spraying into 200 pounds per square inch chamber pressure. The points for the curves were cross-plotted from the curves for heavy fuel oil shown in the insert, and from similar curves for the other fuel oils.

The penetration is seen to increase with the specific gravity and the upward trend of the curves indicates that oils of greater specific gravity than those tested would have still greater effects. From the curves, a heavy oil of 0.90 specific gravity would have 10 per cent greater penetration after 0.003 second than an ordinary Diesel oil of a specific gravity of 0.85. The heavy oil is more viscous than the others, and is not as readily atomized. This makes the spray angle narrower and helps to produce greater penetration.

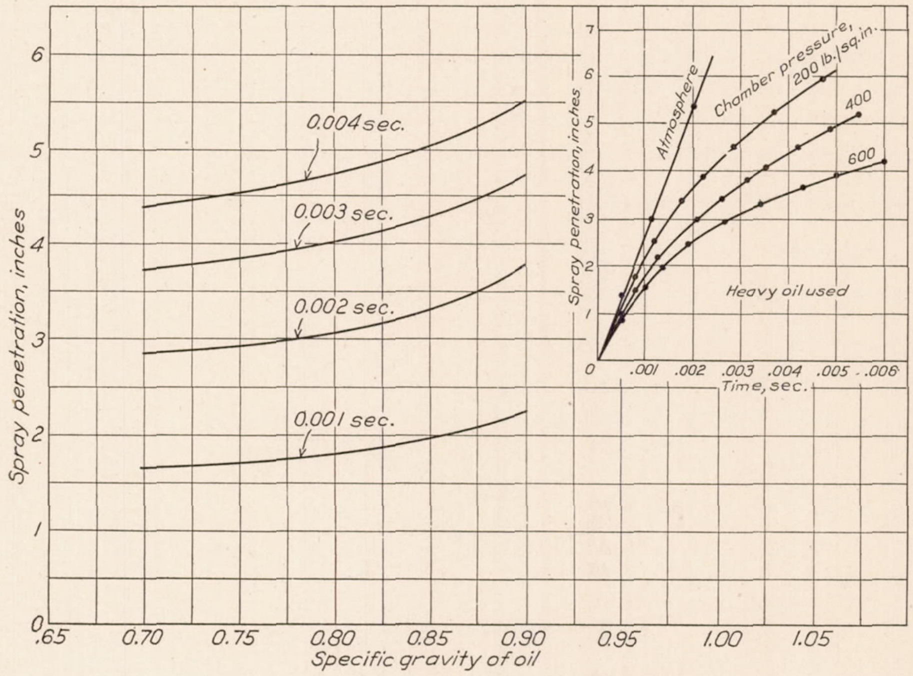


FIG. 10.—Effect of specific gravity of oil on spray penetration

Injection valve No. 7; 23° spiral.
Cylinder orifice, 0.022 inch diameter.
Injection pressure, 8,000 pounds per square inch.
Fuel oil used, gasoline, kerosene, Diesel, and heavy fuel oil of specific gravity 0.705, 0.799, 0.85, and 0.90, respectively.
Air in spray chamber at 200 pounds per square inch.

EFFECT OF VALVE DESIGN

The effect of the groove-helix angle on the penetration, cone angle, and ratio of spray volume to oil volume with a valve injecting into 200 pounds per square inch air pressure is shown in Figure 11. The penetration increases considerably with increase in the angle of the spiral grooves, the 90° or noncentrifugal spray having 60 per cent greater penetration after 0.003 second than does the 23° high-centrifugal spray. The spray angle was decreased from 53° to 23° by this same increase in the groove-helix angle.

To find the relative distribution, and to obtain an indication of the atomization of the spray, the actual spray volumes were computed. The quantities of oil injected with each valve assembly were different; therefore, to put them all on the same basis, the ratios of spray volume to oil volume were computed. These are plotted in Figure 11, and indicate the spray distribution. The distribution was 100 per cent greater for the high-centrifugal than for the noncentrifugal spray.

The effects of varying the ratio of orifice area to groove area from 0.19 to 2.05 upon the spray penetration, cone angle, and the ratio of spray volume to oil volume, with 200 pounds per square inch air pressure, are shown in Figure 12. The penetration increases rapidly as the ratio becomes very small. The ratio was decreased by decreasing the size of the orifice, the groove area being kept constant. Thus the orifice became very small with a small ratio and the rotation

of the jet initiated by the spiral grooves could not continue effectively through this small orifice. The energy which, with a larger orifice, was consumed in rotating the oil went into giving the spray axial penetration in the case of the very small orifice. The spray angle was therefore reduced, as shown by the spray-angle curve. The shape of this curve indicates that the spray angle would not be greatly increased by increase in the ratio beyond 2.0.

The curve at the top of Figure 12 shows the effect of the ratio of orifice area to groove area upon the spray distribution. This curve would indicate that the orifice size has considerable effect upon the spray distribution and possibly atomization.

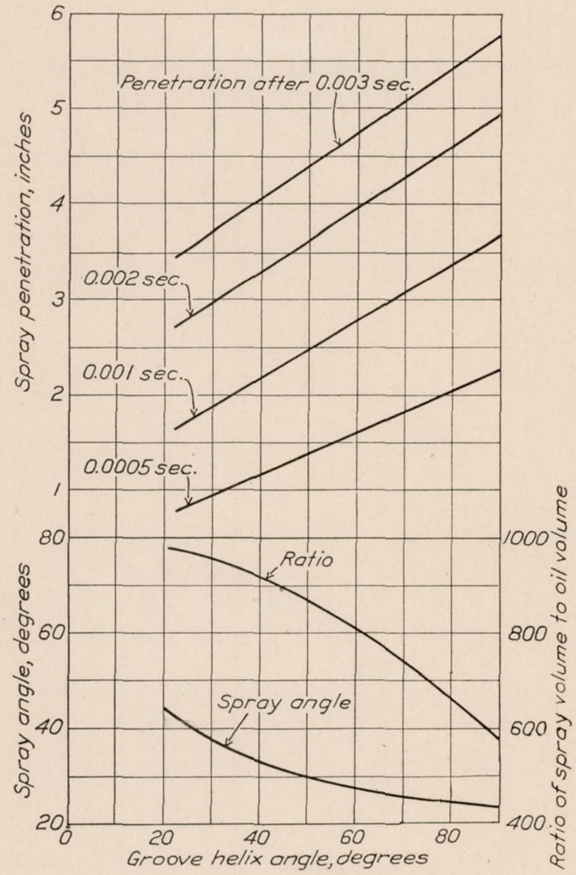


FIG. 11.—Effect of groove helix angle on spray characteristics.

Injection valve No. 7.
Cylinder orifice, 0.022 inch diameter.
Injection pressure, 8,000 pounds per square inch.
Fuel oil used, Diesel oil of 0.85 specific gravity.
Gas in spray chamber, nitrogen at 200 pounds per square inch.

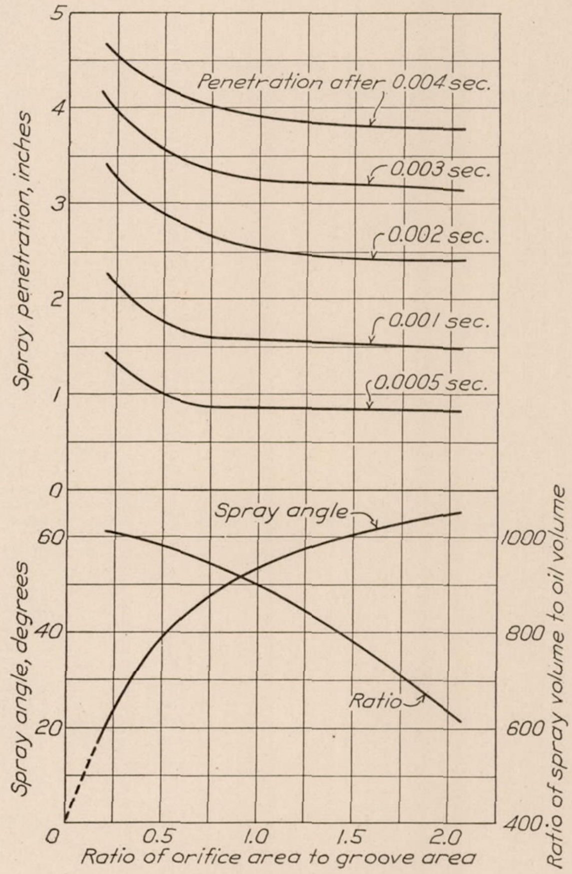


FIG. 12.—Effect of ratio of orifice area to groove area on spray characteristics

Injection valve No. 7; 23° spiral grooves.
Cylinder orifices, 0.012, 0.022, and 0.040 inch diameter.
Injection pressure, 8,000 pounds per square inch.
Fuel oil used, Diesel oil of 0.85 specific gravity.
Nitrogen in spray chamber at 200 pounds per square inch.

CONCLUSIONS

The test results presented in this report are examples of the information which it is possible to obtain by means of the apparatus described. The results show some fundamental effects of the variables investigated. The spray penetration increased directly with the injection pressures. The absolute gas density in the chamber was found to control spray penetration. The spray penetration increased with increase in the specific gravity of the fuel oil used. The spray penetration increased with increase in the groove-helix angle, while the spray angle and ratio of spray to oil volume decreased. On the other hand, the spray penetration and ratio of spray to oil volume decreased with increase in the ratio of orifice area to groove area, but the spray angle increased. By means of these and other investigations, data are obtained which

make possible the design of injection valves to produce sprays for various sizes and shapes of engine combustion chambers.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *May 25, 1927.*

REFERENCE

1. Joachim, W. F., and Beardsley, E. G. Factors in the Design of Centrifugal Type Injection Valves for Oil Engines. N. A. C. A. Technical Report No. 268, 1927.

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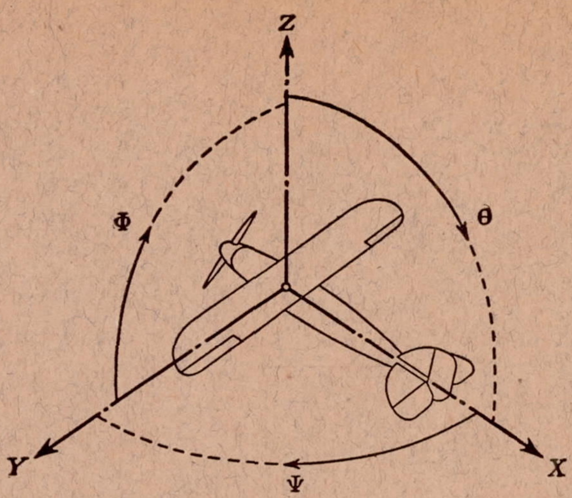

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_L=\frac{L}{qbS}\quad C_M=\frac{M}{qcS}\quad C_N=\frac{N}{qfS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p_e, Effective pitch
p_g, Mean geometric pitch.
p_s, Standard pitch.
p_v, Zero thrust.
p_a, Zero torque.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slip stream velocity.

T, Thrust.
Q, Torque.
P, Power.
(If "coefficients" are introduced all units used must be consistent.)
η, Efficiency $= T\,V/P$.
n, Revolutions per sec., r. p. s.
N, Revolutions per minute., R. P. M.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 HP = 76.04 kg/m/sec. = 550 lb./ft./sec.
1 kg/m/sec. = 0.01315 HP.
1 mi./hr. = 0.44704 m/sec.
1 m/sec. = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft